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ELECTROACTIVE POLYMER ACTUATORS

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Defence R&D Canada

DEFENCE RESEARCH ESTABLISHMENT ATLANTIC

Contractor Report

DREA CR 2001-053

May 2001

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104-06943/

Abstract

A voltage potential applied across a thin, non-conducting, elastomeric membrane results in the attraction of two charged surfaces, compression of the elastomer and a resulting increase in its length. Devices based on this concept have been called dielectric actuators. This report presents results of preliminary work to fabricate and characterize dielectric polymer actuators, as well as a simple theoretical model of their behaviour. Dielectric actuators based on cast thermoplastic polyurethane films were prepared with brushed-on graphite powder as electrodes. Strains of up to around two percent were measured. This strain corresponds to a stress of approximately 150 kPa. The voltage/strain relationship followed a parabolic relationship as predicted by theoretical considerations. Actuators with similar strain values were prepared by forming longer films and rolling them into tubes.

Résumé

L'application d'une tension électrique à travers une membrane mince d'un élastomère non conducteur produit l'attraction de deux surfaces chargées, la compression de l'élastomère et, conséquemment, un accroissement de sa longueur. Les dispositifs conçus selon ce principe sont connus sous le nom d'actionneurs diélectriques. Le présent rapport contient les résultats de travaux préliminaires visant à fabriquer et à caractériser des actionneurs diélectriques polymériques, ainsi que ceux portant sur un modèle théorique simplifié de leur comportement. On a fabriqué des actionneurs diélectriques à base de films thermoplastiques en polyuréthane coulé, en utilisant de la poudre de graphite appliquée à la brosse comme électrodes. On a effectué des mesures pour des déformations pouvant atteindre environ 2 %. Cette valeur de déformation correspond à une contrainte d'environ 150 kPa. La relation tension électrique/déformation est de forme parabolique, tel que prévu par les paramètres théoriques. On a aussi fabriqué des actionneurs possédant des propriétés de déformation similaires en coulant des films plus longs et en les enroulant sous forme de tubes.

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Executive summary

Background

A voltage potential applied across a thin, non-conducting, elastomeric membrane results in the attraction of two charged surfaces, compression of the elastomer, and a resulting increase in its length. These "dielectric actuators" offer a number of potential advantages over other types of polymeric actuators, including high elongation combined with high frequency and fast response. Dielectric actuators are interesting candidates for active vibration damping applications for marine engines where they can combine both passive as well as active damping characteristics. These actuators are still in their infancy and require the development of both a theoretical understanding of their static and dynamic properties as well as the development of fabrication processes.

Principal Results

This report presents results of preliminary work to fabricate and characterize dielectric polymer actuators, as well as a simple theoretical model of their behaviour. Dielectric actuators based on cast thermoplastic polyurethane films were prepared with brushed-on graphite powder as electrodes. Strains of up to around two percent were measured. This strain corresponds to a stress of approximately 150 kPa. The voltage/strain relationship followed a parabolic relationship as predicted by theoretical considerations. Actuators with similar strain values were prepared by forming longer films and rolling them into tubes. A simple parallel plate capacitor model was used to show that the maximum stress exerted by a dielectric actuator is independent of the Young's modulus of the dielectric elastomer, but is proportional to the square of the dielectric breakdown voltage, and to the first power of the dielectric permittivity. Non-uniformity of the film thickness made it impossible to determine if the experimental strain-thickness dependence was in accordance with the model.

Significance of Results

This study showed that it is possible to produce dielectric actuators based on polyurethanes in both film and rod form. The voltage dependence of the strain was in accordance with the simple model presented.

Future Work

The objective of this work was to build and test rudimentary dielectric actuators. If funding is available, future work will focus on the development of hybrid active/passive vibration isolation systems using dielectric actuators, and/or low frequency active sonar transducers.

Szabo, J., 2001. Electroactive Polymer Actuators, DREA CR 2001-053 Defence Research Establishment Atlantic

Sommaire

Contexte

L'application d'une tension électrique à travers une membrane mince d'un élastomère non conducteur produit l'attraction de deux surfaces chargées, la compression de l'élastomère et, conséquemment, un accroissement de sa longueur. Ces « actionneurs diélectriques » offrent un certain nombre d'avantages éventuels par rapport aux autres types d'actionneurs polymériques, dont un important allongement, combiné à une fréquence élevée et à une réaction rapide. Les actionneurs diélectriques sont des candidats intéressants comme matériau d'amortissement actif des vibrations de moteurs marins, car ces applications combinent leurs caractéristiques d'amortissement passif, de même que celles d'amortissement actif. Ces types d'actionneurs en sont encore à leurs premiers balbutiements et il faut donc approfondir les connaissances théoriques portant sur leurs propriétés statiques et dynamiques, et élaborer des méthodes de fabrication.

Principaux résultats

Le présent rapport contient les résultats de travaux préliminaires visant à fabriquer et à caractériser des actionneurs diélectriques polymériques, ainsi que ceux portant sur un modèle théorique simplifié de leur comportement. On a fabriqué des actionneurs diélectriques à base de films thermoplastiques en polyuréthane coulé, en utilisant de la poudre de graphite appliquée à la brosse comme électrodes. On a effectué des mesures pour des déformations pouvant atteindre environ 2 %. Cette valeur de déformation correspond à une contrainte d'environ 150 kPa. La relation tension électrique/déformation est de forme parabolique, tel que prévu par les paramètres théoriques. On a aussi fabriqué des actionneurs possédant des valeurs de déformation similaires en coulant des films plus longs et en les enroulant sous forme de tubes. On a utilisé un modèle simplifié de condensateur à plaques parallèles pour démontrer que la contrainte maximum exercée par un actionneur diélectrique ne dépend pas du module de Young de l'élastomère diélectrique, mais qu'elle est proportionnelle au carré de la tension de claquage diélectrique, et directement proportionnelle à la permittivité diélectrique. Le film avait une épaisseur irrégulière, ce qui n'a pas permis de déterminer s'il existe une accord entre les résultats relatifs à la dépendance déformation-épaisseur et le modèle.

Importance des résultats

Les résultats de la présente étude démontrent qu'il est possible de fabriquer des actionneurs diélectriques à base de polyuréthanes, sous forme de film et sous forme de tige. La dépendance entre la déformation et la tension électrique appliquée est conforme au modèle simplifié utilisé.

Futurs travaux

Le but des présents travaux était de fabriquer des actionneurs diélectriques de base et de les mettre à l'essai. Si le financement le permet, les travaux futurs seront centrés sur la mise au point de systèmes hybrides d'isolation des vibrations, de nature active et passive, à l'aide d'actionneurs diélectriques, et/ou de transducteurs sonars actifs à basse fréquence.

Szabo, J., 2001, Actionneurs à base de polymère électroactif, CRDA CR 2001-053, Defence Research Establishment Atlantic.

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1.0 INTRODUCTION

Recent developments in smart materials and structures have pointed to the need for a broader range of actuating materials. There are currently two main classes of actuating materials - piezoelectric materials, characterized by high frequency response but very small movements, and shape memory alloys, characterized by a very slow response but relatively large movements. In some applications, the fact that shape memory alloys are activated only by heat can be a disadvantage.

Polymeric actuators are an emerging class of materials, which offer the potential to fill the performance gap between piezoelectric materials and shape memory alloys.

The following are the main classes of electroactive polymers:

- Piezoelectric. Known for a long time but with somewhat limited application due to the low movements typical of piezoelectric actuators and actuation forces lower than these of ceramic piezoelectric actuators.

- Hydrated membranes and hydrogels. Ionic movement across a membrane causes material movement and therefore shrinkage of one of the sides and expansion on the other resulting in gross bending of the sample. These actuators are being explored in a number of centres around the world. The advantage of these actuators is relatively low actuation potential (can be as low as 1 volt). The forces exerted by these actuators tend to be low due to the low stiffness of the material itself. The actuators have to be wet to be active and there is no good way to prevent them from drying. Reported elongations of these systems are of the order of a few percent.

- Electrostrictive. The overall dimensional change is caused by the alignment of bulky side chains in an electric field.

- Dielectric. A voltage potential applied across a thin, non-conducting, elastomeric membrane results in the attraction of two charged surfaces, compression of the elastomer and a resulting increase in its length. The electrode applied to the surface of the elastomer also has to be elastomeric. Elongation up to 200% and frequencies of the order of 1 kHz has been reported for electrostatic systems.

Dielectric systems, which are the subject of this project, offer a number of potential advantages:

- high elongation combined with high frequency and fast response,

- they are not tied to a specific chemistry, their performance can be tailored to a specific application,
- different shapes can be formed (membranes, multi-layer membranes, fibres, ropes etc.), and
- they can potentially be manufactured by standard plastics processes such as continuous extrusion.

Because of their design versatility, dielectric systems offer good potential for a variety of applications such as active vibration control. This system also allows for combining of both active and passive vibration damping in a single device.

The objective of this project was to prepare and characterize an electroactivated polymer system based on the dielectric principle, in both film and rod forms.

2.0 BACKGROUND

2.1 Technology Review

Work on dielectric polymeric actuators has been carried out for the last few years, mainly by SRI in the United States, and more recently in Denmark. A number of papers were presented at the Smart Structures and Materials Meeting of the SPIE. References are given in Appendix A.

The following comments characterize this work:

- The focus of the work seems to have been achieving higher and higher elongations. This has resulted in using materials with low stiffness and high creep which are not the best for actuation.
- The majority of the work focused on developing applications at the expense of materials and understanding the response of these systems. Applications which have been prototyped include small robots, flat panel speakers, membrane pumps and electrical generators.
- The materials used are off-the-shelf commercial materials. There does not appear to have been any effort to develop or select appropriate materials.
- Most actuators are in the form of thin films although some work has been done on multi-layer systems.

2.2 Theoretical Background

Dielectric actuators are based on Coulomb's law which states that two opposite charges attract. In a vacuum the force of attraction is:

$F = Q^2/4\pi e_o r^2$

Where F is the force between the two charges, Q is the charge, e_o is the dielectric constant (permittivity) of vacuum, and r is half the distance between the charges.

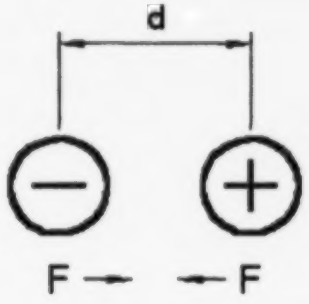

Figure 1 - Attraction of opposite charges

When a dielectric material is inserted between the charges, the force decreases to

$F = Q^2/4\pi e_o e r^2$

Where e is the relative permittivity of the dielectric material separating the charges.

The force acting on the plates of a parallel plate capacitor (which is what a dielectric actuator is) under an applied voltage V is

$F = Ae_o eV^2/2d^2$

where A is the area of the capacitor and d is the distance between the plates, or, expressed in terms of the pressure

$P = e_o eV^2/2d^2$

When pressure P is applied to an elastic material, it shortens in the direction of this pressure (stress) by

$$\varepsilon = P/Y$$

where ε is strain (compression), defined as the dimensional change divided by the original dimension, and Y is the Young's modulus of the material.

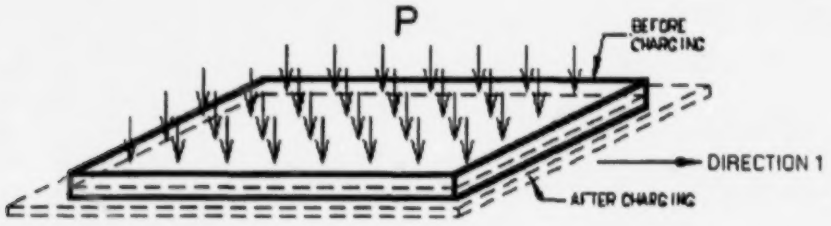

Figure 2 - Expansion of dielectric under pressure of applied voltage

While being compressed in one dimension, the sample will also elongate in the dimensions normal to the direction of the pressure. This elongation is given by

$$\varepsilon_l = \mu\varepsilon$$

where ε_l is the elongation in direction 1 and μ is Poisson's ratio, representing the ratio of the elongations in the two directions. For an isotropic elastomer, μ is approximately 0.5.

Combining the last three equations, we obtain expressions for the elongation as well as the stress exerted by the dielectric actuator:

$$\varepsilon_l = \mu e_0 e V^2/2Yd^2$$

$$P_l = \mu e_0 e V^2/2d^2$$

These equations describe the response of an electrostatic actuator to an applied voltage. The maximum effect is achieved at the maximum applied voltage which is defined by the dielectric breakdown strength of the dielectric (V_b) and is usually expressed as the breakdown voltage (V_d) of a material of unit thickness.

The dielectric breakdown voltage for a sample of thickness d is then

$V_d = V_b d$

One has to keep in mind that this equation might not hold for very thin films or films where manufacturing flaws govern the dielectric breakdown strength.

Substituting this equation into the expressions for pressure and elongation we obtain the maximum effects:

$\epsilon_{max} = \mu e_0 e V_b^2/2Y$

$P_{max} = \mu e_0 e V_b^2/2$

The following conclusions can be drawn from these considerations:

- Both elongation and stress are directly proportional to the second power of the applied voltage and inversely proportional to the second power of the thickness of the elastomer.
- Both elongation and stress are proportional to the relative permittivity. As the relative permittivity increases, the amount of charge stored at a given voltage increases; however, the force between two given charges decreases.
- The strain is inversely proportional to the Young's modulus of the material, but the stress is not.
- Both stress and strain are proportional to Poisson's ratio. It is expected that an actuator in rod form would be a much more effective actuator, since the elongation would only be in one direction (longitudinal) rather than in two. The Poisson's ratio can be also modified by orienting the polymers as well as by using oriented fibre composites.
- The maximum effects do not depend on the thickness of the film used but only on the dielectric breakdown strength of the dielectric. There is, of course, an advantage in thinner dielectrics as they allow for operation at lower voltages.

The above equations describe in a rudimentary way the performance of a dielectric actuator under static conditions. The assumptions made are:

- The elastomeric material is perfectly elastic, which is roughly true at low deformations but not at high deformations.

- The electrode layer has no thickness or stiffness. In reality, this layer has specific mechanical properties which have to be taken into account.

- Deformations and forces are only caused by attraction of the charges. In reality, some materials might also exhibit additional electrostrictive effects.

In order to properly describe and model dielectric actuators, the following have to be considered:

- static properties as described above, but also including the properties of the electrode layer, and
- dynamic response, which will depend on
  - complex mechanical properties of the dielectric,
  - complex electrical properties of the dielectric,
  - the ability to conduct the charge in and out of the actuator, and
  - changes in properties due to temperature change.

Understanding all of these parameters and their effect on actuator performance will eventually lead to the design of practical systems.

3.0 EXPERIMENTAL

3.1 Material Selection

Materials for the two components were sourced based on the following requirements:

- Elastomer - non-conductive, no pinholes, high dielectric breakdown strength, high dielectric constant, low hardness.

- Facings - low stiffness, electrically conductive.

Because of the abbreviated project schedule, ease of fabrication was one of the more important selection criteria.

The following materials were selected and acquired:

Name	Manufacturer	Type	Hardness (Shore A)	Dielectric Constant	Dielectric Strength (kV/mm)
FC2123	Dyneon	Fluorinated rubber	71	5.7	40
THV 220	Dyneon	Fluorinated rubber	44	5.7	62
Elastosil RT 601	Wacker	2 component silicone	45	3.1	23
Pellethane 2103-70A	Dow	Thermoplastic polyurethane	72	7.3	25
PLV 6034	Pelseal	2 component fluoroelastomer		3.1	40
SIFEL 5701	Shin Etsu MicroSi	2 component fluorosilicone	71	3.1	23

We carried out preliminary film casting experiments and eventually selected the thermoplastic polyurethane (Pellethane 2103-70A) for further work. The main reason for this selection was the ease of preparing films by simple casting, without the need for curing.

3.2 Fabrication of Actuators

3.2.1 Design of Spin Coater

Dielectric actuators require that the elastic material used as the dielectric has a high dielectric strength. The dielectric strength is a function of the inherent material properties as well as of the manufacturing process. Our original concept was to use a centrifugal casting technique in which the film would be subject to centrifugal force while being cast, thus removing gas bubbles from the casting. A centrifugal caster was designed and built and is shown in Appendix B, Figure B-1. Initial experiments carried out with the caster indicated that the dimensional accuracy of the casting drum was inadequate, resulting in non-uniform films. Since modifying the apparatus and developing a practical casting procedure would take several weeks, and since the caster would allow us to produce only single films, we decided to produce films by simple casting. This was followed by careful examination of the surface and selection of areas without imperfections.

3.2.2 *Film Preparation*

Films were prepared according to the following procedure:

1. Dissolve polyurethane in N,N-dimethyl formamide (8% by weight).

2. Cast a film of the desired thickness on glass using a drawdown applicator to control thickness. Glass plates (14" x 14") are buffed with S.C.Johnson® Paste Wax to facilitate removal of films after drying.

3. Dry films at 60°C for at least 8 hours.

The original objective was to produce actuators based on 25, 50 and 100 micron films. During experimentation we experienced dielectric breakdown at low voltages with thin films and were unable to measure elongation for these. We then attempted to produce films having thicknesses of 50, 100, and 150 microns. The thickness values reported herein are a rough average of several measurements taken on each film.

3.2.3 *Preparation of Electrodes*

The polyurethane film contained electrically conductive graphite powder layers on both sides. The end tabs used for the electrical connections contained a conductive layer on one side only. A small amount of uncoated film was left around the active area to prevent electrical shorting around the edge.

The polyurethane film was prepared as described above. A mask for coating the conductive layer was cut from 200 μm Mylar film. The polyurethane film was visually inspected for defects under low magnification (<5X) and an area relatively free of defects was selected. A mask was placed on the surface of the film and graphite powder (Timrex KS6, TIMCAL Ltd.) was swabbed on the surface. The graphite powder adhered to the surface due to slight surface tack. Surface resistivity was determined to be 10.4 kΩ/square using this technique. The film was then stripped from the base plate, reversed, and the second electrode was applied in the same fashion. After trimming the edges, the actuator was ready for testing. A schematic drawing of a film actuator is shown in Figure 3.

"Rod" actuators were prepared by "rolling" film actuators laminated with a non-conducting barrier film (a polyurethane film having the same dimensions as the actuator film). A schematic drawing of a rod actuator (before rolling) is shown in Figure 4.

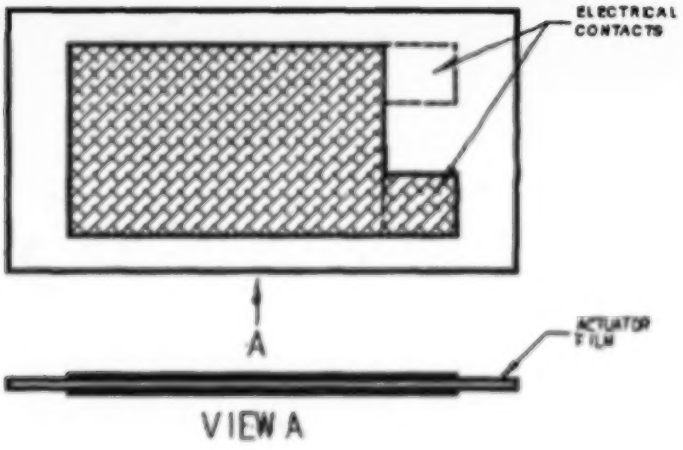

Figure 3 - Top and cross section views of a film actuator

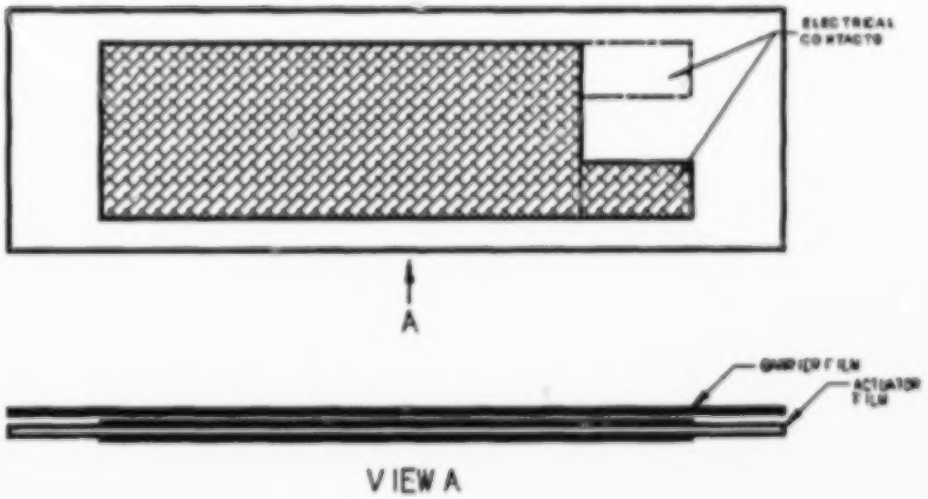

Figure 4 - Top and cross section views of a rod actuator

In order to prepare a rod actuator, the actuator film was first coated with graphite on both sides. Contact cement (Lepage Pres-Tite™ Green), reduced 80% with water, was applied to one side of the barrier film. When dry, the side coated with adhesive was laminated to the graphite-coated film. The other side of the barrier film was dabbed with talc to prevent the film from sticking to itself as it was rolled up. The laminated film was rolled onto a 3.175 mm steel mandrel with the talc side in contact with the mandrel. The mandrel was removed from one end, and a plastic drinking straw was inserted about 25 mm into the rolled up film and attached with black electrical tape. This was repeated on the other side. The rod actuator could now be mounted in the actuation chamber for testing.

3.3 Actuation Experiments

3.3.1 Design of Actuation Chamber

We designed and built an actuation chamber (see Appendix B, Figures B-2 and B-3) mainly because of the hazards associated with testing using high voltages. The charge was generated by a high voltage power supply (Del Electronics Corp, Model No. RLPS 10-60R, MII B05243). Samples were attached by two clips which also conducted charge into the sample. A weight (typically 125 g) was hung from the bottom of the sample. The chamber has an interlock which disconnects the power supply when the door is open. The elongation of the sample was measured using a cathetometer (MII B03157), a non-contact visual measuring device.

3.3.2 Measurement of Elongation

Measurements of film elongation were conducted by setting the power supply to a specific voltage, turning the power on, and measuring the distance the lower edge of the sample had travelled. This was repeated to check the reliability of the measurement. The voltage was increased gradually and elongation measurements were carried out until dielectric breakdown of the elastomer occurred. The maximum voltage which could be applied was limited by the dielectric breakdown strength of the polymer. The measured extension was used to calculate percent elongation (strain) of the active area of the electrode.

It was our original intention to measure elongation on films of 25 μm, 50 μm, and 100 μm thickness. However, the thinner films were destroyed at low voltages by arcing before any change in the length could be measured. We then attempted to produce films having thicknesses of 75, 100, and 150 microns. We had difficulty producing films with a uniform thickness. For example, a film cast to have a thickness of 100 μm ranged in thickness from 75 μm to 125 μm. The thickness values reported herein are a rough average of several measurements taken on each film.

The data showing the effect of applied voltage on elongation are given in Appendix C, Table C-I and Figures C-1 to C-3.

Since elongation is proportional to the square of applied voltage ($\varepsilon = \mu e_o e V^2/2Yd^2$), the data for each of the three film thicknesses was fitted to a curve having the form

Elongation = a x (Applied Voltage)^2

where a is a constant that depends on film thickness.

The value of a was determined for each film thickness:

Sample No.	Average Film Thickness (microns)	a
01-05-8518-107	84	1.590×10^{-9}
01-05-8660-7-3	100	1.136×10^{-9}
01-05-8660-9/12	135	1.144×10^{-9}

Theoretically, strain is also inversely proportional to the square of the distance between the plates, or film thickness in this case. In our experiments we did not observe this dependence. Since the thickness of each film was not consistent, the "distance between the plates" could not be defined accurately. We could not, therefore, relate the elongation behaviour of the film to a specific, known film thickness.

3.3.3 Mechanical Properties of Films

In order to calculate the force exerted as a result of the applied voltage, it was necessary to determine the stress/strain behaviour for Pellethane 2103-70A and relate it to the applied voltage/strain behaviour for each actuator. Tensile stress was measured in accordance with the method described in ASTM D 882-97, "Tensile Properties of Thin Plastic Sheeting". A film of Pellethane was cast and specimens cut from the film using a die cutter. The length of the specimens was parallel to the draw-down direction. Three specimens were tested for each sample.

Test Conditions

Specimen dimensions	25.4 mm wide x 254.0 mm long
Gauge length	152.4 mm
Grip distance	152.4 mm
Separation rate	15.24 mm/min
Ambient conditions	23°C and 50% R.H.

The following equipment was used for the testing:

Equipment	MII Number
Instron tensile tester	A06347
50 pound load cell	B01134
Digital thickness gauge	A10983

The stress/strain results are shown in Appendix D, Table D-I and Figure D-1.

Assuming that the relationship between stress and strain is linear, the equation representing this relationship can be determined from the graph of tensile stress vs strain. The equation takes the form of Hooke's law:

Tensile Stress = Y x Strain

where Y is the Young's modulus for the material. For Pellethane 2103-70A, the value of Y was determined to be 7.275×10^3 kPa from Figure D-1.

3.3.4 Calculation of Stress/Voltage Relationship

Knowing the relationships between applied voltage and elongation and stress and elongation allows us to calculate the relationship between applied voltage and stress. The stress/voltage curves represent the load bearing capacity of these actuators.

For example, for the 100 μm film,

Elongation = $1.136 \times 10^{-9} \times (\text{Applied Voltage})^2$

and

Stress (kPa) = $7.275 \times 10^3 \times$ Strain.

Combining these two equations yield the relationship for stress (force) in terms of applied voltage:

Stress = $7.275 \times 10^3 \times 1.136 \times 10^{-9} \times (\text{Applied Voltage})^2$

or

Stress = $8.264 \times 10^{-6} \times (\text{Applied Voltage})^2$

The calculated force is shown as a function of applied voltage for the three film thicknesses in Table D-II.

The results agree with the theory in that the elongation was found to be proportional to the square of applied voltage. However, we did not observe the theoretical relationship between elongation and the inverse square of film thickness (distance between electrodes) for the reasons outlined above.

3.3.5 Actuator Rod

The same procedures were followed to determine the behaviour of actuator rods. Actuator rods were prepared as described in section 3.2.3, and mounted in the actuation chamber for measurement of elongation as shown in Figure B-2. Elongation as a function of applied voltage is shown in Figure C-4.

The rods were found to exhibit similar elongation behaviour as the films, as shown in Table C-I. As well, the calculated force was very close to that of the films over the measured applied voltage range (Table D-II).

4.0 FUTURE WORK

This project was meant as an introduction to the development of active (or hybrid active/passive) vibration control systems using dielectric actuators. The objective of this work was to build and test fairly rudimentary dielectric actuators. An actuator used for active vibration damping would most likely be a "rolled" actuator. A large actuator would be built from an elastomeric film containing compliant electrodes. The following activities are envisaged leading to this development:

4.1 Modelling

- Static response
- Dynamic - combining material properties, with electrical considerations
- Thermal - heat generation and its effect on performance.

4.2 Materials and Fabrication

- Selection and fabrication of materials. At this time we envisage formulating with crosslinked polyurethanes.

- Fabrication technique. A process will be required for casting long and thin films without imperfections, as well as for applying the conductive electrodes.

- Electrode material. An electrode material will be required. It might be a very soft polyurethane highly filled with conductive material(s). Both high electrical conductivity and low stiffness are required.

- Fabrication of actuators. A process for consolidating films into appropriate actuators as well as for attaching electrodes will be required.

4.3 Drivers

Drivers will be required for dynamic application of voltages to the actuators.

4.4 Characterization

The following actuator performance characteristics will have to be determined:

- static response
- dynamic response
- mechanical (not actuated) performance
- durability.

4.5 Vibration Control Strategy

Dielectric actuators as envisaged here will have some passive damping characteristics. Active vibration damping will be superimposed on passive damping. The capacitance of the actuator will change due to deformation. It might be possible to use this change as a feedback control tool. The overall approach to the use of these actuators for active vibration damping of engines has to be developed.

APPENDIX A

References

(1 Page)

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2. G. Kofod, R. D. Kornbluh, R. Pelrine, P. Sommer-Larsen, "Actuation Response of Polyacrylate Dielectric Elastomers", Smart Structures and Materials 2000, Electroactive Polymer Actuators and Devices, SPIE Conference, March 2001.

3. R. Pelrine, R. D. Kornbluh, J. Eckerle, P. Jeuck, S. Oh, Q. Pei, "Dielectric Elastomers: Generator Mode Fundamentals and Applications", Smart Structures and Materials 2000, Electroactive Polymer Actuators and Devices, SPIE Conference, March 2001.

4. P. Sommer-Larsen, J. C. Hooker, G. Kofod, K. West, M. Benslimane, P. Gravesen, "Response of Dielectric Elastomer Actuators", Smart Structures and Materials 2000, Electroactive Polymer Actuators and Devices, SPIE Conference, March 2001.

5. R. Pelrine, R. D. Kornbluh, Q. Pei, J. Eckerle, R. Heydt, S. Shastri, P. Sommer-Larsen, "Applications of Dielectric Elastomer Artificial Muscles", Smart Structures and Materials 2000, Electroactive Polymer Actuators and Devices, SPIE Conference, March 2001.

APPENDIX B

Experimental Apparatus

(3 Pages)

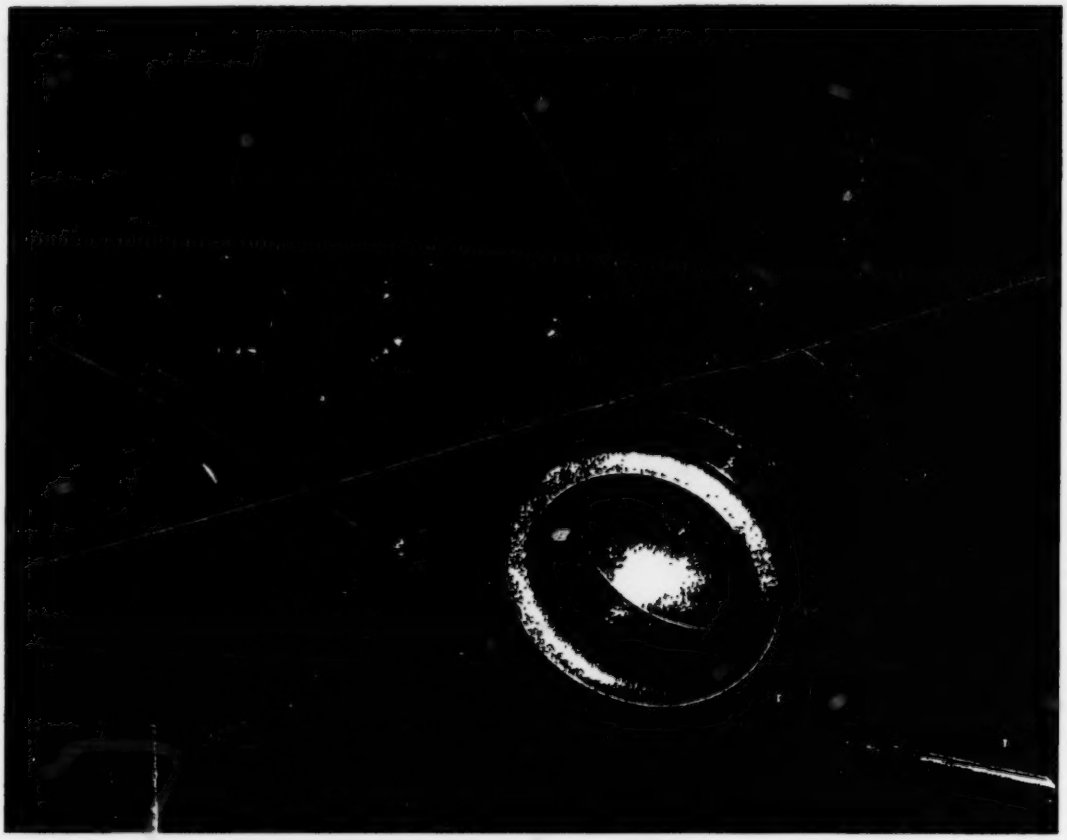


Figure B-1 - Centrifugal caster

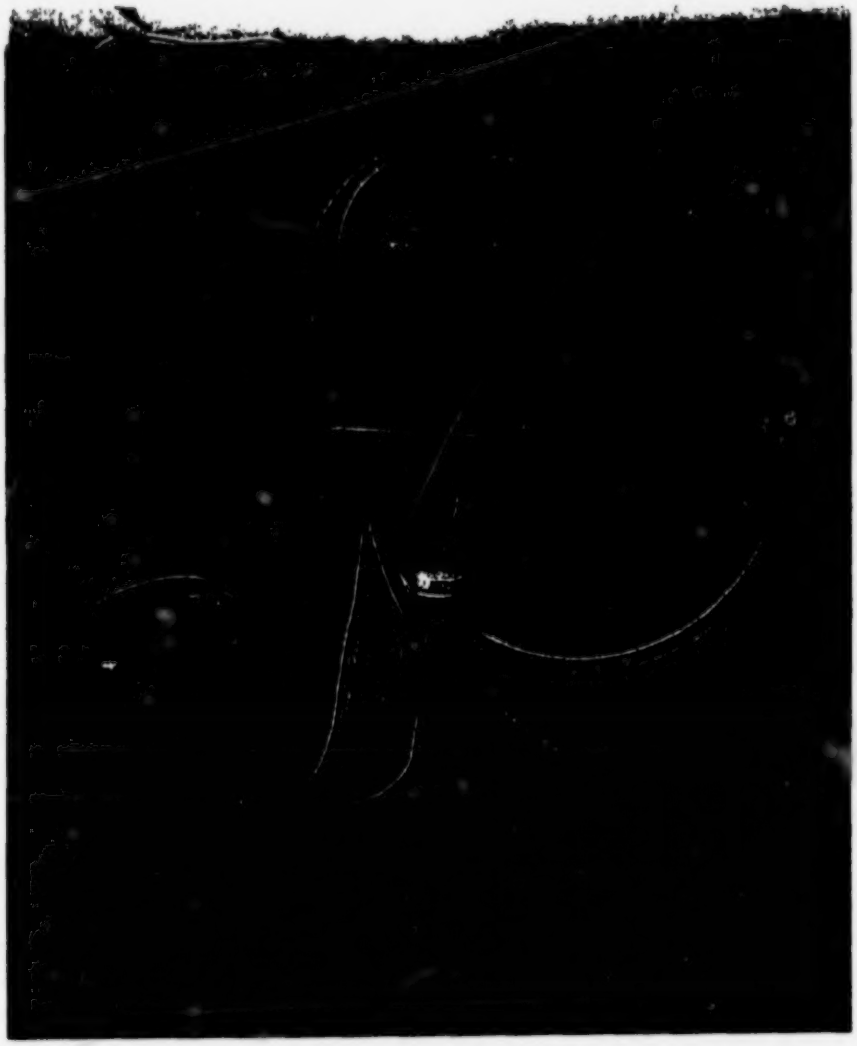


Figure B-2 - Actuation chamber showing film actuator in position for testing

Figure B-3 - Actuation chamber showing rod actuator in position for testing

APPENDIX C

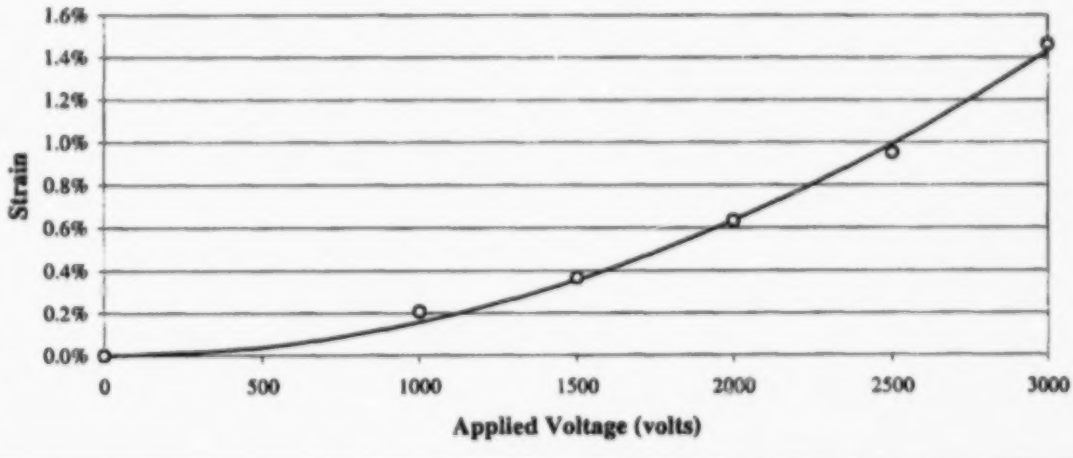
Effect of Applied Voltage on Strain

(5 Pages)

Table C-I
Effect of Applied Voltage on Strain

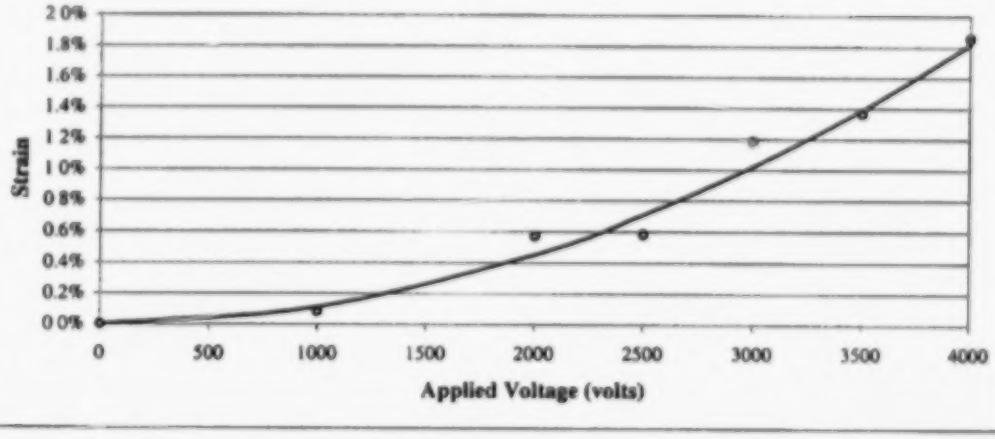
	Strain (%)			
Applied Voltage	**84 μm Film** 01-05-8518-107	**100 μm Film** 01-05-8660-7-3	**135 μm Film** 01-05-8660-9/12	**100 μm Rod** 01-05-8518-111
0	0.00	0.00	0.00	0.00
1000		0.09		
1500	0.21			0.29
2000	0.37	0.57	0.39	0.50
2500	0.63	0.59	0.73	0.75
3000	0.95	1.18	0.87	1.04
3500	1.46	1.37	1.12	
4000		1.86	1.44	
4500			1.60	

Figure C-1
Effect of Applied Voltage - 84 μm Film



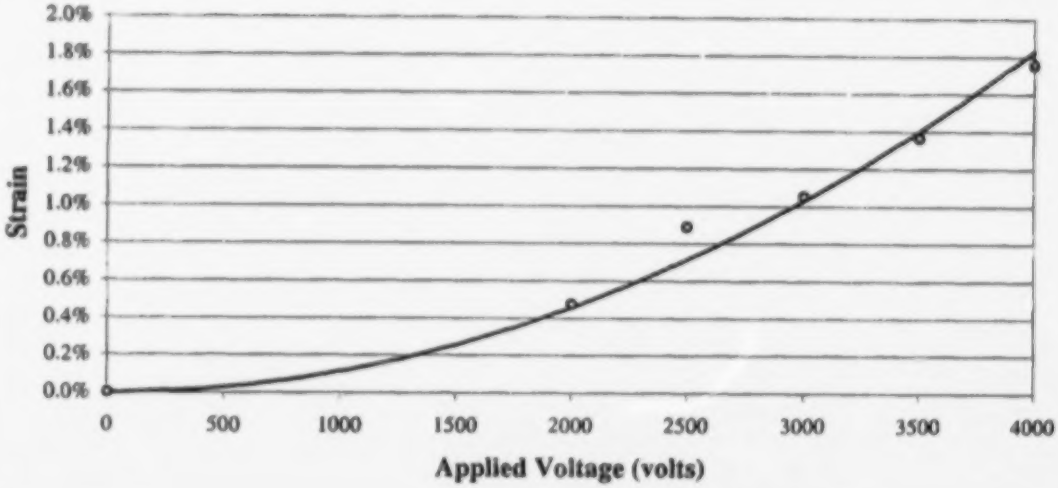
$$\text{Strain} = 1.59 \times 10^{-9} \times (\text{Applied Voltage})^2$$

Figure C-2
Effect of Applied Voltage - 100 μm Film



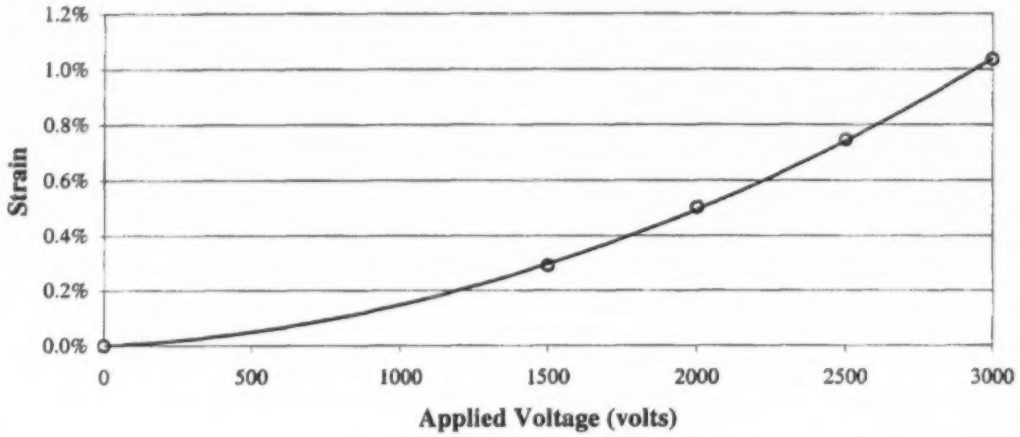
$$\text{Strain} = 1.136 \times 10^{-9} \times (\text{Applied Voltage})^2$$

Figure C-3
Effect of Applied Voltage - 135 μm Film



$$\text{Strain} = 1.144 \times 10^{-9} \times (\text{Applied Voltage})^2$$

Figure C-4
Effect of Applied Voltage - 100 μm Rod



Strain = $1.22 \times 10^{-9} \times (\text{Appplied Voltage})^2$

APPENDIX D

Stress/Strain Testing

(3 Pages)

Table D-I
Stress/Strain Data for Pellethane 2103-70A

Sample No. 01-05-8518-90	
Strain (%)	**Tensile Stress (kPa)**
0.0	0.0
0.05	4.3
0.1	7.2
0.2	15.2
0.3	21.8
0.4	30.3
0.5	38.3
0.6	46.1
0.7	53.5
0.8	61.4
0.9	68.6
1.0	75.2
1.1	82.0
1.2	88.1
1.3	97.3
1.4	104.7
1.5	111.6
1.6	119.7
1.7	126.6
1.8	133.7
1.9	140.4
2.0	146.6
2.1	153.9
2.2	159.9
2.3	165.4
2.4	172.9
2.5	181.3
2.6	187.9
2.7	194.1
2.8	200.1
2.9	206.9
3.0	215.0

Figure D-1
Stress/Strain Behaviour of Pellethane 2103-70A

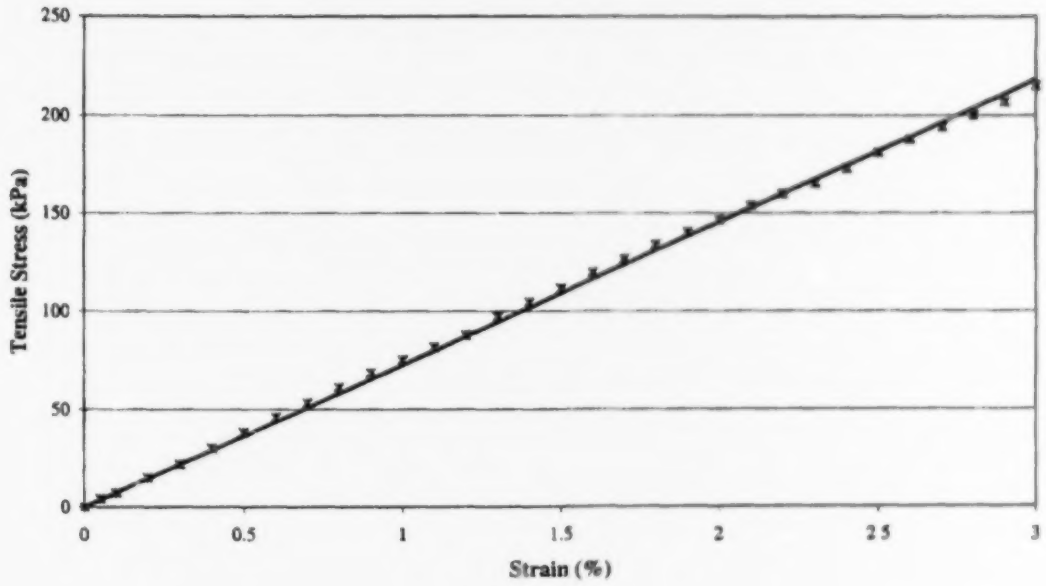


Table D-II
Effect of Film Thickness on Calculated Stress

	Stress (kPa)			
Applied Voltage	**84 μm Film** 01-05-8518-107	**100 μm Film** 01-05-8660-7-3	**135 μm Film** 01-05-8660-9/12	**100 μm Rod** 01-05-8518-111
0	0	0	0	0
500	3	2	2	
1000	12	8	8	
1500	26	19	19	20
2000	46	33	33	36
2500	72	52	52	56
3000	104	74	75	80
3500	142	101	102	
4000	185	132	133	
4500	234	167	169	

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Jacob Leidner and David Hacker

5 DATE OF PUBLICATION (month and year of publication of document)	6a NO OF PAGES (total containing information Include Annexes, Appendices etc)	6b NO OF REFS (total cited in document)
May 2001	32	5

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8 SPONSORING ACTIVITY (the name of the department project office or laboratory sponsoring the research and development Include address)

Defence Research Establishment Atlantic
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9a PROJECT OR GRANT NO (if appropriate, the applicable research and development project or grant number under which the document was written Please specify whether project or grant)	9b CONTRACT NO (if appropriate the applicable number under which the document was written)
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A voltage potential applied across a thin, non-conducting, elastomeric membrane results in the attraction of two charged surfaces, compression of the elastomer and a resulting increase in its length. Devices based on this concept have been called dielectric actuators. This report presents results of preliminary work to fabricate and characterize dielectric polymer actuators, as well as a simple theoretical model of their behaviour. Dielectric actuators based on cast thermoplastic polyurethane films were prepared with brushed-on graphite powder as electrodes. Strains of up to around two percent were measured. This strain corresponds to a stress of approximately 150 kPa. The voltage/strain relationship followed a parabolic relationship as predicted by theoretical considerations. Actuators with similar strain values were prepared by forming longer films and rolling them into tubes.

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